DESIGN OF A LOW-POWER AUTOMATIC WIRELESS MULTI-LOGGER NETWORKING DEVICE

by

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Abstract

Design of a Low-Power Automatic Wireless Multi-Logger Networking Device

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Virtually every industry and discipline (e.g., mining, pharmaceutical, construction, agriculture, reclamation, etc.) is finding applications for wireless data acquisition for monitoring and managing processes and resources. Two sectors, namely agriculture and environmental research, are seeking ways to obtain distributed soil and plant measurements over larger areas like a watershed or large fields rather than a single site of intensive instrumentation (i.e., a weather station). Wireless sensor networks and remote sensing have been explored as a means to satisfy this need. Commercial products are readily available that have remote wireless options to support distributed senor networking. However, these systems have been designed with a field engineer or technician as the target end-user. Equipment and operating costs, device specific programming languages, and complex wireless configuration schemes have impeded the adoption of large-scale, multi-node wireless systems in these fields. This report details the development of an easy-to-use, ultra-low power wireless datalogger incorporating a scalable, intelligent data collection and transmission topology. The final product can interface to various sensor types including SDI-12 and uses an LCD display to help simplify device setup.

(68 pages)

Taking the technical out of new technology.

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Chapter 1

Introduction

This chapter contains a brief introduction to the rationale and design behind the development of the *Acclima DataManager*. Supporting background in wireless data acquisition, along with a discussion of current issues existing in agriculture and environmental monitoring is also presented. The *Acclima DataManager* aims to resolve these issues presented and provide a low-power cost-effective platform to further intelligent resource management and control.

1.1 Background

In the agricultural and environmental work of today, critical biological and physical processes are monitored and recorded using sophisticated measuring equipment. Common measurements referred to by these interest groups include, but are not limited to, soil water content, soil and air temperature, relative humidity, soil CO_2, soil O_2, soil pH, soil electrical conductivity, and rain water. Of these characterizations, subsurface processes have traditionally been more elusive to observe. The corrosive nature of soil and its varying properties of composition have made it difficult to feasible obtain accurate measurements (less than five percent) of any properties in this medium for years and one location. Some in these fields have also been interested in long term acquisition of soil characteristics for the purpose of closed-loop management of property and conservation of natural resources.

Acclima Incorporated is an irrigation control company that specializes in precise water management. One of Acclima's market interests includes agricultural and environmental research markets. Therefore, Acclima undertook to fund a large portion of this work. Another key contributer was Aquarius Brands. Large-scale agricultural producers have expressed to Acclima and Aquarius Brands the desire to not only have automatic equipment

for supporting crop water and nutrient management, but also to obtain a descriptive, spatial measure of the function and efficiency of these management systems. Researchers and environmental analysts are searching for ways to increase spatial resolution of subsurface soil properties to assist in characterizing and modeling below-ground processes in the large (e.g., watersheds and basins).

1.2 Problem Definition

One method suggested by Morse and Kramberis is to use remote sensing and satellite imaging to infer the desired properties from pictures taken from low-earth orbit [2, 3]. This method is based on Evapotranspiration (ET) models and has received much attention during the last twenty years. It has excelled in many areas like forest resource management, crop yield estimation in precision agriculture, and analyzing the environmental effects of urbanization guiding city planners. However, it has produced little in terms of useful subsurface property estimation in agriculture. The cost of access, infrequent access times, complexity, and estimation error inherent to such approaches also deter agricultural producers from choosing this option. Researchers like Verhoest, on the other hand, have made use of this technology but desire a more timely and reliable method. He claims that more ground data is needed to continue refining their subsurface property estimation techniques [4].

The more common approach employed by producers and researchers alike involves the use of weather stations as a static means of collecting environmental data, and separately paying for soil testing laboratories to examine the more elusive soil properties. A single on-site weather station, similar to the one seen in fig. 1.1, can cost thousands to tens of thousands of dollars. These systems are also based on ET models and estimate the amount of water in the soil from observable air characteristics. Due to the complexity of these systems, most require experienced technicians trained to operate the measurement equipment and manage extensive databases. In the ambit of academia, professors employ students studying in technical fields to manage the complex field equipment used in their research. The drawback for universities is that student turnover is very high and research is put on hold to train new research assistants every one or two years.

Fig. 1.1: Weather station located at TWDEF, Cache, UT.

The above mentioned approaches are in practice all around the world. For ground-based systems, using wireless data links is becoming the norm for remote data collection sites. Cost and installation time concerns drive the deviation from wired-based communications. The complexity added by introducing wireless into standing systems, coupled with the need for potentially adding thousands of network nodes, is quickly pushing current technologies and methodologies to their limit. The market currently offers no solution that addresses the challenges associated with large network management and simplifying the implementation of a scalable, highly spatial measurement system.

1.3 Desired Equipment Features

Considering the challenges with current approaches to large scale subsurface soil characterization, Acclima Inc. and investor Aquarius Brands decided to probe whether there would be a need or desire for new instrumentation. They approached produce farmers from California and Washington and soil and agricultural researchers at Utah State University and Boise State University. They received encouraging feedback and proceeded to ask what device properties and characteristics they thought lacked in some of the currently available equipment. Acclima then proceeded to present proposals for a new device that would satisfy these needs.

The results from this informal poll illustrated that these two interest groups are looking for a rugged, simple to use, power-efficient logger that has a built-in intelligent wireless option. Naturally, they also did not want to pay thousands for one logger because the nature of their work or research incorporates tens to hundreds of these devices. The following are key requirements assembled from these discussions.

- **Simple to Use -** targeted toward producers, not engineers
- **Low Power -** able to run on inexpensive batteries for at least one growing season (i.e., about six to eight months of operation)
- **Low Cost -** a distributed system with a per-node cost of $800 or less is acceptable

- **Radio Access -** wireless system that is reliable up at least a half a mile and supports a one-step network setup and data routing
- **Sufficiently Rugged -** resistant to environment, rough handling, and vandalism
- **Automatic Centralized Data Collection -** All data in a network of devices must be collected and stored at one central location
- **Versatile Sensor Interface -** Support wide array of readily available sensors interfaces like analog voltage or current measurements, digital pulse-width and pulse-frequency measurements, and SDI-12 measurements.

Of note among this list is the requirement that this device must have radio access. This feature alone is the most sought after and, ironically, introduces the most complexity. This feature has pushed the cost of some existing systems into the thousands of dollars. It also introduces the need for a network management level, which has frustrated and deterred many producers and researches.

1.4 Proposed Objectives

Given the need for a new system, the author partnered with Acclima and Aquarius Brands who provided funding to develop a new market-ready wireless data-logging platform called the *Acclima DataManager* which:

1. Offers, through the integration of ultra low-power electronic devices and on-board power management, a longer battery life than any existing equivalent product on the market.
2. Supports a wide variety of sensors with analog, digital, and SDI-12 interfaces in a competitive, low-cost package.
3. Facilitates a dynamically integrated sensor-network approach to environmental sensing and data communication by making use of the ZigBee (IEEE 802.15.4) Mesh interface and supporting runtime reconfiguration of ZigBee network personalities. This will allow any product purchased to be configured as a coordinator, router, or endpoint.

4. Allows non-engineers to easily access advanced logger features through a simple, yet powerful LCD driven user interface and PC software.

This report describes in detail the design of an ultra low-power ZigBee-enabled data-logging device targeted for agricultural and environmental monitoring. Beyond general funding, Acclima also initially provided the market study, development tools, and code libraries that assisted with the development of the LCD and MCU flash drivers. All other development described in this report constitutes the project effort. Acclima engineer David Anderson assisted in advising the author during the generation of hardware and firmware modules. He also coordinated the author's work with the concurrent development of the PC interface software and the custom enclosure development.

1.5 Scope of Impact

With the completion of this new generation of advanced data loggers with integrated intelligent wireless network management, approaches and methods to environmental monitoring that were previously unattainable now can be considered. To the fullest scope, a multi-tiered data fusion effort can fully be realized. The benefits of this effort include early error and automatic statistical outlier detection, local and global analysis of correlative data, and an adjustable field of view for collaboration. One *DataManager* can support multiple sensor types delivering a more complete picture of the processes being observed. Then data from one site can readily be combined with data from one to hundreds of local collection points. Finally, this compilation can be submitted to strengthen fine-grain, spectral remote sensing algorithms by providing a sensor network of geospatially located sites that can be fused with satellite data. This diverse dataset can eventually pave the way to truly automatic robots that can "see" and interact with its environment to till or harvest crops completely unaided.

Another feasible application now apparent is the detailed mapping of watersheds that feed water to many of the normally arid regions that dominate the western half of the United States. Many water sheds have already been geologically mapped and soil construction and

formations in these areas are well documented. Using this information, researchers and hydrologists have generated models of water flow and sediment transport to forecast the amount of water available from the land's reserves and the effect of heavy rain during flooding seasons. Now a system of networked loggers that can be directly accessed to ascertain the saturation levels of the soil increasing the reliability of said predictions.

Chapter 2

Subject Review

This chapter discusses in detail the background issues presented in section 1.2. It will do this by presenting documented examples of current methods used in environmental sensing projects. Common models used to estimate environmental properties will then be presented followed by a discussion illustrating the need for more collaborative analysis efforts. Finally, a survey of commonly used products used to measure and store data for these projects will be presented and their features discussed. These discussions will illuminate the apparent need for a new product.

2.1 Current Methods of Subsurface Property Estimation

The two methods commonly used to estimate soil properties using ET are ground-based weather stations and remote sensing. Ground stations, termed the conventional approach in fig. 2.1, measures the ET potential and calculate a new estimated ET value based on a previous soil moisture value. Remote sensing uses satellite imaging to observe surface moisture flux and a previous value for soil moisture to arrive at the estimated ET. This resulting ET value is then inserted into a model and a new soil moisture value is obtained [1,5]. Possible models available to extrapolate soil moisture from ET are classified as budget [6], semi-dynamic [7], and dynamic [8]. Any ET-based estimates always have a processing lag inherently associated with its final output. This delay is caused by the need to acquire the previous ET value. Processing also is not done on site because the algorithms are to computationally complex to run on these power limited devices. This offsets the moisture solution by an entire interval. One ET interval is about one day for the conventional method and three to fourteen days for the remote sensing approach [9]. Using the best ET methods to date, the best accuracy attained after extensive data processing

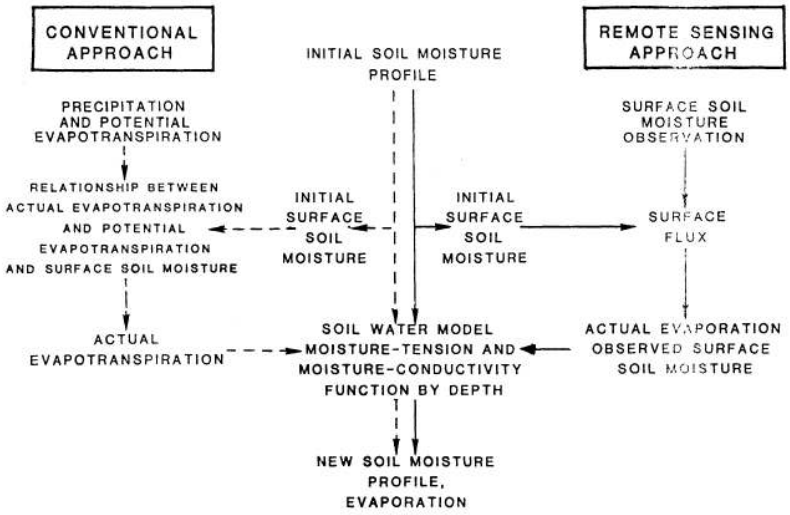

Fig. 2.1: Two common approches to extract soil moisture from ET (figure proccured from Bernard et al. [1]).

still reflects 6% error [4]. The model inaccuracies coupled with the lag and interval delays introduce too much error for some to grow crops or to report solid scientific numbers using these methods. However, Verhoest et al. [4] claims that more ground data is needed to continue refining their subsurface property estimation models.

2.2 Current Methods of Environmental Property Determination

The basic building block to any ground system designed for data acquisition is the single site measurement and control device commonly termed in the literature as a "datalogger." The term datalogger refers to many device classes from weather station controllers to a freezer temperature recorder. Some of their features include but are not limited to analog and digital measurement capabilities, onboard data storage, and basic RS-232 or advanced communications links like the GOES satellite data-link. Dataloggers form the backbone of most weather stations and can be interfaced with sensors to measure the subsurface properties directly [10, 11]. For a small scale network of loggers (e.g., less than 20 devices), wired systems using RS485 or 900MHz point-to-multipoint radio connections are most common. Many of these systems can be found at USU and other universities. In particular, Greenville

farm, located in Logan, Utah, has a system that falls under this category that uses point-to-multipoint radios to tie six weather stations together [12]. T.W Daniel's Research Forest site, situated in the mountains above Bear Lake, Utah, interconnects sixteen dataloggers using RS485 [13].

On a large scale, systems are connected using TCP/IP, satellite telemetry, or long distance data radios. The Internet provides the ability to connect sites from many different places around the world. Any system desiring to use this link needs only conform to the TCP/IP specification and operate as a web-application or web-database. Campbell Scientific Incorporated sells the NL100 Ethernet Adapter to enable their products to be accessed using a TCP/IP network or Internet [14]. In more remote areas of the globe where the Internet is not accessible, satellite telemetry (e.g., Iridium, GOES, etc.) is used. One use for Iridium satellites are Dart-II buoys for oceanic weather and tsunami warning systems [15]. The Snotel system used by the NRCS uses Meteor-Burst radios that use VHF band radio waves that bounce waves off of the Ionosphere. This technology is capable of transmitting over 1,000 km [16]. As of June 2003, over 660 Snotel sites were in operation [11]. Organizations like the National Oceanic and Atmospheric Administration (NOAA) collect environmental data from various sources using all of the above mentioned means. NOAA supplies meteorologists and scientists with current weather data through a web database [17].

2.3 The ZigBee Protocol

The methods mentioned above are sufficient to satisfy the need for spatially variant data in the presence of external infrastructure. However, in rural areas the current technologies support localized wired networks or wireless networks with topologies more suited for devices ten miles or more apart [18]. ZigBee, a derivative of IEEE 802.15.4, is a wireless protocol that focuses on highly reliable mesh networks optimized for low data rates and a device grid-size of less than a mile. The protocol was first established in 2001 [19]. In 2006, the first commercail ZigBee compliant radio modules were released. Moving towards 2008, these modules are becoming a popular interface for remote sensors [18].

These new radios are filling the void left by other protocols in medium scale, low-power networking. Devices using ZigBee need little work to setup a self-healing, scalable network [20]. This leaves the host device interfacing with these radios needing only to be programmed with data management and database routines, leaving the network topology to the protocol. The maximum network size is limited by the protocol to be less than 64,000 nodes [19].

2.4 Missing Analysis Opportunities

Sensor networking is the practice of taking sensors and embedding them with intelligent wireless data-links. An artifact of sensor networking is data fusion [21]: the combining of multiple measurements and data types to infer an attribute generally beyond a single source or source type. Some algorithms developed in data fusion include localization and directed diffusion algorithms, distributed tracking in wireless ad hoc networks, and distributed classification using local agents [22, 23]. Data fusion algorithms can be used to increase accuracy of noise-prone sensors [24]. Common algorithms use least mean square (LMS) censuses [25], Bayesian [23, 26], and Kalman filter and Dempster-Shafer evidence theory [27]. All of these algorithms provide ways of extrapolating meaningful indicators that can be used in automation and to advance analysis or modeling efforts [28].

2.5 Survey of Existing Product

Various companies specializing in creating products to collect environmental data have produced dataloggers which offer many of the features described in section 1.3. Four of these businesses and their currently available products will be discussed in sections 2.5.1-2.5.4. All of these loggers work well and have established their place in providing services to their respective target communities. All of theses products will be reviewed using section 1.3.

2.5.1 Campbell Scientific Incorporated

Campbell Scientific [29], a company based in Cache Valley, Utah, is a world renowned maker of rugged data logging and measurement equipment. They have offices and produc-

Fig. 2.2: Figure of the Campbell Scientific's CR200 series datalogger.

tion facilities in Utah, Washington DC, and Canada. They are also the closely partnered with other well known companies in the fields of environmental data systems and computing (e.g., Decagon, Apogee Instruments, and Juniper Systems). Their interests are broad and they provide over 200 different products. Upon inspection of Campbell's exhaustive data logger portfolio, the logger selected as the closest candidate to satisfy the requirements discussed in section 1.3 is the CR200 series datalogger.

The CR200 series logger, as seen in fig. 2.2, was designed by Campbell to be their smallest logger and therefore well-suited in cost and size for remote measurements. It can store up to 32,000 data points and hold six kilobytes of program code. CRBasic or Edlog are Campbell's programming languages that are cross-compiled and sent to the loggers. The CR200 series uses Campbell's proprietary PakBus OS that supports addressable networking through a wired or wireless physical layer. It features five digital or single-ended (SE) analog ports with 12-bit voltage measurement ports, each with a 0-2500mV maximum range and 0.6mV resolution. It also has two pulse measurement ports, one SDI-12 port, two 2.5V or 5V excitation ports and one switched port for battery voltage. All units come with an integrated 12V lead-acid battery charger and a RS-232 communication port. Select units have integrated 900 MHz and 2.4 GHz ISM spread-spectrum radios ('206, '211, '216). Lastly the device has an ESD rating of 15KV, temperature ratings of -20 and 70 Celsius

and has been proven by years of field work.

Addressing the requirement list discussed in section 1.3, this logger does support multiple power modes that enables it to conserve battery life. Its power modes are as follows: $.2mA$ inactive, $3mA$ active with no radio, and $20mA$ to $75mA$ active with radio. These are satisfactory power specifications. The logger also satisfies the integrated radio specification and database requirements as well. However, the logger fails the ease of use stipulation. To use a Campbell logger, one must know basic electrical principals and wire up the system based on these principals. Then one must learn the CRBasic or Edlog programming languages. To establish a wireless network, the user must then manage the PakBus protocols on every logger in the system. All of these tasks are technical in nature. This device does not have a built-in user interface. This logger also fails the ruggedness requirement because it isn't weatherproof, and requires a separate enclosure to ensure continued operation in any of the rated conditions. Finally, it fails on cost. A user must purchase the logger and the proprietary software to interface to the logger and other Campbell Scientific devices. The logger cost is $630 (2007), together with batteries, enclosure, and software is over $1,400. Software costs only apply to the first system, so the site cost of a system using a CR200 is around $1000 per node, falling outside the stated cost requirement.

2.5.2 Sutron Systems

This Virginian company [30] is also a world renowned maker of rugged data logging and measurement equipment. They specialize in building very rugged datalogging platforms that communicate using high power RF and satellite communication. Some of the equipment manufactured by this company has been deployed in harsh environments such as the Himalayas, South American rain forests, and Antarctica. Sutron manufactures six different logging platforms with various sensor interfaces most of which were designed for large amounts of instrumentation at one location.

The 8210 logger (see fig. 2.3) was selected as the closest match for this application. It boasts 62,000 to 190,000 volatile measurement readings possible and an external PCMCIA to expand memory size to a gigabyte. One of three methods can be used to program

Fig. 2.3: Picture of Sutron's 8210 datalogger.

this device. One is by using the front panel. A simple 1 X 40 character display and six buttons are available to navigate the device's basic configurations. There is the GUI Xpert software that is an easy and convenient method to adjust configurations and download data. There is also the option to use the Tiny Basic programming language for more specialized programs that are beyond the standard configurations. The 8210 logger comes with twenty digital IO, five counter inputs, and eight 13-bit analog inputs with five volt SE or 2.5 volt differential options. Ports are available for SDI-12 interfacing and five volt and twelve volt excitation. The logger comes with a 12V, $6.5Ah$ internal battery capable of ninety days of unattended operation. It also has charge regulators for direct interfacing to a solar panel. One externally accessible and two internally accessible communications ports are also available on this model. This way, a user could communicate with a satellite, a local wireless network, and a PC simultaneously. The device has a temperature rating of -50 to 60 C.

The above stated capabilities make this system is a fantastic system for logging just about everything anywhere around the world. Its capabilities allow it to operate an entire weather station singularly and to take advantage of satellite telemetry. However, the types of application and possible markets target by this study do not need all the versatility provided by this device. This system has an integrated user interface and a PC interface,

but the integrated display is only used to display status and generic operations. To access the system's complex feature set, a programming language and computer must be used. The logger can be battery powered for an extended duration, qualifying it in terms of the low-power requirement. The 8210 does have radio options, but to use them one must have the technical expertise to know what kind of wireless connection he/she wants and how to tell the logger how to do it. The logger is enclosed and is rated for harsh environments satisfying the ruggedness requirement. One logger costs $2000-$5000 and therefore falls significantly outside the desired cost requirement. In summary, this is a great system that satisfies every requirement except simplicity and cost.

2.5.3 Automata Incorporated

Automata Inc. [31], a company located in California, designs and manufactures devices that incorporate data logging, telemetry, software interfaces, and sensors. For their radio units they offer satellite, infrared, narrow-band, and spread spectrum radios. They also offer RS-232, telephone, and fiber optic communications. Automata has been in business for 32 years and have received many consumer awards for their Mini series and FC Field Controller units.

The product from this company selected for review is the Mini-SS Logger (see fig. 2.4). It was designed with a multi-nodal network in mind. This datalogger is one that closely resembles an irrigation controller except for the added features of being able to log data. For this reason devices come standard with little onboard log memory. In addition, an extra $128K$ of volatile memory can be added to improve the storage capacity above standard. Sensors can be measured and recorded based on the following methods: timer (interval based), event, and interrogation (on demand). The system comes with four digital IO ports that can source enough current to actuate a valve or be used as a pulse counter. The logger has four 10-bit SE $5\,V$ or 0-$1mA$ or 0-$20mA$ measurement ports. No other interfaces exist. This device has one communications port that supports RS232, SPI, and I2C at 1200 though 19,200 Baud. For power, this device uses a $12\,V$ battery with the option of solar power.

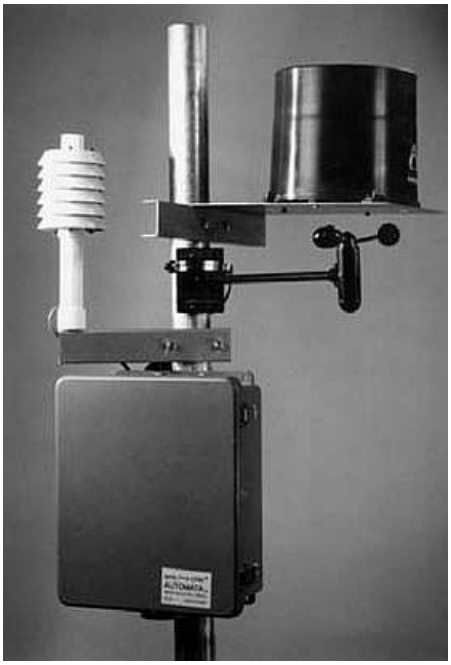

Fig. 2.4: Figure showing Automata's Mini-SS logger.

This system compares favorably to the desired specifications. It is simple to use and configure. However, the radio and database requirements fail because the logger has no inherent support for an automatic multi-node network of loggers or controllers. Although one can easily setup local measurements, the effort and expertise required to setup a wireless network with data storage/routing management would be a job for a technician, not a producer. The logger comes with a qualified enclosure and therefore satisfies the ruggedness constraint. It satisfies the power requirement because it uses only $5mA$ when active and $.2mA$ when sleeping. However, the system can only operate on battery power for two months unattended with the standard battery supplied at purchase. This system also fails the interface requirement. It only has analog sensor interfaces and does not support digital or SDI-12. The system costs $875 and is therefore on the borderline of the stated cost requirement.

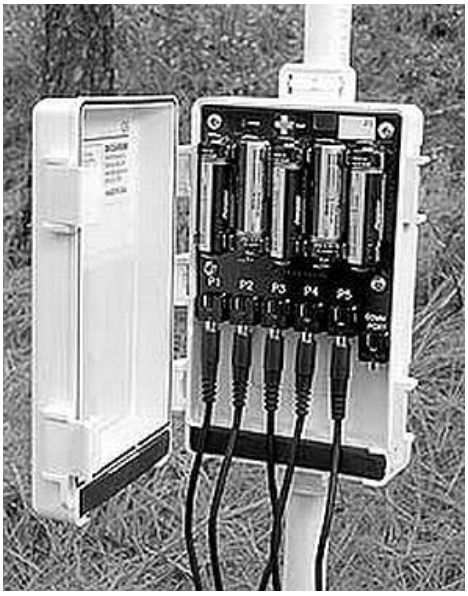

Fig. 2.5: The Em50R from Decagon Devices.

2.5.4 Decagon Devices Incorporated

Decagon Devices Inc. [32], based in Pullman, Washington, has developed over 30 different devices, sensors, and controllers/loggers alike. This company specializes in providing quality products at a competitive cost. Decagon has products available for the following fields: food and pharmaceutical science, geotechnical and civil engineering, environmental research, and commercial irrigation.

Decagon has three loggers in its repertoire designated as Em50, Em50R, and the EM5b. The Em50 and Em50R are identical except for the integrated radio on the EM50R. The EM5b is meant to be an ultra low-cost solution for single site monitoring. After inspecting these loggers, the Em50R, seen in fig. 2.5, was selected as the most applicable candidate for multi-nodal data collection network. It comes in a NEMA rated enclosure to protect it from the weather. The Em50R has ability to store 33,000 non-volatile sensor logs enabling the logger to run for twelve months without overwriting old data. The logger has no direct interface, but the PC interface is very easy to use and configuration can be setup relatively quickly. The radio option for this logger requires further setup and coordination.

The Em50R operates on five AA batteries for a duration of five to six months. Its sensor interface is limited to SE 12-bit analog. A stereo head-phone jack with excitation, signal, and ground is the standard hardware interface for sensors. This requires that the Em50R use Decagon's sensors only. The cost of the system is anywhere from $400 to $600 making it a very reasonable solution cost-wise.

The Em50R does appear to be an excellent solution for multi-site monitoring. As seen above, the logger satisfies the low-power, cost, ruggedness, and radio requirements. It does not satisfy the necessary interface capability because it does not support SDI-12 or digital sensors. It also does not allow for any other sensors to be used with this system. Lastly, it does not support any data-basing features like automatic data routing and storage. A significant effort in design is required to make centralized storage possible.

2.6 Summary of Product Reviews

Various products from several manufactures that specialize in the collection of agricultural data have been evaluated. All systems were compared to the list of specified requirements. Every one of the products discussed in sections 2.5.1-2.5.4 satisfies the power requirements and all can interface to a type of radio. However, none of these products deliver a complete networked system with all the features expressed in section 1.3. All of these loggers work well and have their place in providing services to their respective target communities. However, no currently available product supports all the required set of features for distributed networking at the desired cost point. Although all the products offer various forms of wireless communication, none of them establish a network, create data routing paths, or store data in a central location automatically. Therefore, a need exists to develop a system that has been targeted to distributed networking.

Chapter 3

Product Definition

This chapter includes details on how the product requirements were further refined from section 1.3 and how the design of a new *DataManager* was approached and decomposed into various sub-components.

3.1 Design Requirement Survey

Discussions between the author, Acclima, and other stakeholders resulted in a more complete list of requirements for a new logger platform, enumerated below:

1. The device must be able to run on commonly available and inexpensive AA-, C-, or D-cell battery power for a period of eight months to a year. The general consensus is that is must last a growing season. For some producers in California, that is all year round.

2. The device must support auxiliary power from external batteries or $6/12\,V$ solar power. The device will therefore have a power input port that can handle at least $15\,VDC$.

3. The device must support variable switched power terminals to supply sensors with power. Many sensors need excitation voltages to perform measurements. Other sensors need different voltage levels than what field site battery can supply. Still other sensors can draw too much current if connected to a battery directly. Consequently, "variable" is interpreted as being able to supply $6\,V$, $9\,V$, $12\,V$, and $15\,V$ at $500mA$.

4. A single device must not cost more than $800, with a target cost of $600.

5. Each device must come in a weather proof enclosure and have a built-in lock. This requirement has two purposes. One is to reduce the cost of installation by not requiring

a separate enclosure. The second is to curb the damage done by rough handling or vandalism.

6. The device must support all of the following interface options: one SDI-12 communication port, three analog input ports, and two digital I/O ports. The analog port must support 0-20mA current measurement and an auto-ranging voltage measurement capable of measuring zero to ten volts with 12-bit accuracy.

7. The device must support an RS232C serial interface so as to connect to a PC or long distance radio. Some discussion was invested into incorporating a USB port instead of an RS232 port. USB is fast becoming a more common interface then RS232, but USB uses more power and was therefore discarded with the caviot that if a processor could be found that supports USB, it could be added as another supported interface.

8. The device must contain a real-time clock (RTC) with battery-backup for unbroken operation for longer than five years of shelf life.

9. The device must support programmable logging intervals with one minute resolution. All sensors are expected to be able to measure at or within this interval.

10. The device must support a common flash memory card interface for extended memory applications and virtual device networking (VDN).[1]

11. The device must have an embedded ZigBee Mesh radio to support a scalable inter-device network for automatic data routing for centralized data storage. The device must support multiple network personalities to make possible the easy integration of this device anywhere in the network. The ability to change the radio's function eliminates the need for Acclima to provide specific coordinator, router, or endpoint loggers.

12. The device must have two easy-to-use methods for configuring the device. One of these ways is to use a LCD driven user interface as a direct way to access device function

[1] VDN is a way to view key files form multiple devices without actually connecting to the real-time network. An image of the device is stored to the memory card.

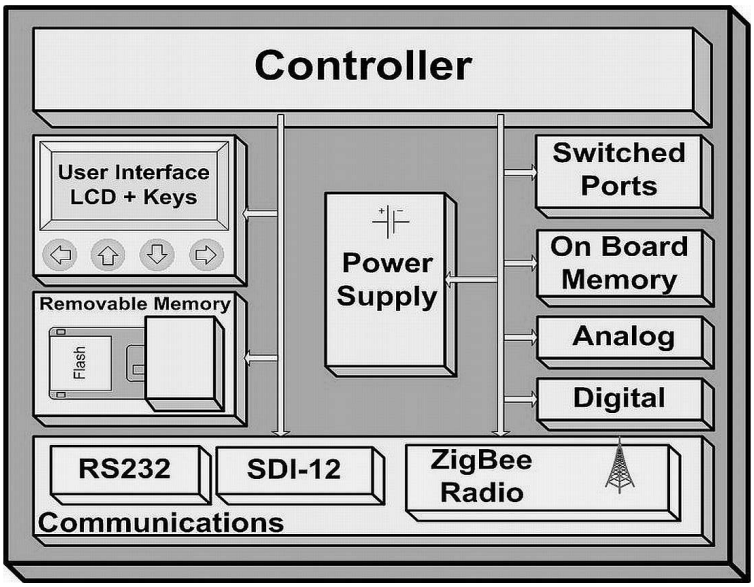

Fig. 3.1: Depiction of the general hardware design.

and to verify correct device operation. This requirement coupled with the memory card requirement allows an operator to forgo using a computer to download data and adjust device settings. The other way is through the PC software. This software should be able to interface to a logger or a network of loggers and be designed to database the data collected by all nodes in a given system.

Good design practice dictates the use of separation of concerns and simplification or elaboration of requirements in the design to achieve a solution that meets all the above stated requirements. The rest of this chapter will discuss in detail how the design specifics were defined through analysis and elimination.

3.2 Hardware Platform Breakdown

Figure 3.1 gives a high level modular decomposition of the logger hardware. Modularity helps minimizes the impact of design changes by iterative revisions through localizing the impact of changes to individual modules. Each module is required to be as self-contained as possible. A module's interface is restricted to simple interface points, through which data exchange occurs. There is a common power bus for the entire logger that is not represented

here. All modules depicted in fig. 3.1 directly tie to the controller and were specifically selected to satisfy the requirements listed in section 3.1. Specifics on the elaboration of the requirement on a module-to-module basis will be shown in sections 3.2.1 - 3.2.1.

3.2.1 Power Supply Module

The purpose of the Power Supply Module is to interface with external power and reliably provide power to the rest of the platform's subsystems. It must satisfy requirement **1**, **2**, **3**, and **8**. To do this, the module must accept a 3.0-6.0 VDC at 600mA battery input, an auxiliary power input required to tolerate up to 15 VDC at 600mA, and a 3.3 VDC backup battery input. The output requirements consist of: controller logic power with 3.3-3.6 VDC at 300mA, SDI-12 communications power with 5.0 VDC at 20mA, and 6.0, 9.0, 12.0, and 15.0 VDC at 500mA sensor power. This module must support unbroken power to a real-time clock (RTC) for at least five years. The module must switch between its three inputs seamlessly and be able to detect power failures. The entire power supply must consume less than 20μA when in sleep mode and 0μA in backup power mode.

3.2.2 Controller Module

The Controller Module is the most complex of all the hardware modules in the device. For large embedded systems, this module could consist of 10,000 processors. However, to balance the cost vs. performance requirements for the *DataManager*, the size and scope of the controller subsystem must be limited to a single microcontroller unit (MCU) solution. An MCU contains a processor core or CPU and a wide variety of peripherals like battery supervisory circuits, timers, RAM and ROM memory, and I/O ports.

After some considerable analysis, the designers concluded with the following subset of the general requirements. This module must support:

1. A RTC that uses less than 5μA. This feature must interface directly with the power module's backup battery. 5μA will sustain the RTC for longer then five years without power.

2. High- and low-frequency crystal support with dynamic clock rate selection. The processor's clock rate is one of the biggest contributors to power draw. The ability to turn off crystals and/or cores or even to slow down their speed is crucial in a low-power design.

3. At least 48K of flash memory. The designers calculate that this application's code will fit in this memory size. Flash was selected because of its wide availability and its ability to be reprogrammed in system. This last feature makes it the perfect selection for non-volatile configuration storage and supporting code that can be re-flashed with an upgrade.

4. At least 2K of RAM. It is difficult to find an 8-bit or 16-bit MCU supporting more than 2K of RAM and 60K of Flash. A better solution would consist of a processor with more RAM which still satisfies the other requirements.

5. At least four general purpose timers to realize communication, event, and interval timing requirements.

6. At least 60 general purpose I/O pins with an additional 14 capable of raising externally generated interrupts, an additional six capable of 12-bit analog-to-digital capturing, and an additional three capable of event capture or direct compare with timers.

7. At least two Universal Synchronous Asynchronous Receiver Transmitters (USARTs) for RS-232 communication and two Serial Peripheral Interface (SPI) ports with separate pins for operation. These are necessary for interfacing to on-board memory, external memory, RS-232 computer port, and the radio module.

8. The cost of the controller module must be less than $10.00. This cost includes the MCU, two crystals, and supporting components.

3.2.3 SDI-12 Communications Module

The SDI-12 module is the first out of three installments that aim to satisfy the general interface requirement. This module must meet SDI-12 V1.3 specifications [33]. Therefore,

12VDC power, ground, and a $5\,V\text{-}TTL$ bidirectional data port must be supported. The SDI-12 module must support nine sensors while using the standard set of device addresses (universal 0 and 1-9). The device must support one port and have individual configurations for all nine sensors. These configurations must support multiple power settings and start up delay parameters.

3.2.4 Analog Measurement Module

The analog module is the second installment that aims to satisfy the general interface requirement. It must have two different measurement modes: current loop and single-ended (SE) voltage measurement modes. In current loop mode, this module will need to reliably measure 0-$20mA$ with $2\mu A$ accuracy. In SE voltage mode, the module must support an auto ranging voltage input capable of measuring the following ranges: 0-$1.5\,V$, 0-$2.5\,V$, 0-$6\,V$, and 0-$10\,V$. The module will consist of three powered measurement ports. Individual configuration for the three ports must support multiple power settings and start up delay parameters. There will be no extra support for differential voltage, high resolution, or pre-amplified measurements.

3.2.5 Digital Measurement Module

The digital module is the third and final installment in the design's attempt to satisfy the general interface requirement. Two ports must be supported by this module. Both ports must support separate input sampling with a timer reference, one power port, and have transient and over-voltage protection and be $5\,V\text{-}TTL$ tolerant. The module must support separate configurations for both ports.

3.2.6 Switched Power Module

The Switch Power Module controls the output and timing of all the power ports. This module satisfies the general requirement that all sensors can be powered by the device. One port must be associated with every SDI-12 and analog port, as well as one for the two digital ports. All ports must be capable of outputting 6-$15\,VDC$ with an output current of

$500mA$ at $6\,VDC$ and $200mA$ at $15\,VDC$. P-channel open-drain outputs must be used on all switches.

3.2.7 Serial Communications Module

The general requirements state that the device must be configurable by PC or by long distance data radios. The Serial Communications Module must therefore support this function. The common RS-232C specification [34] is widely used today. To support this protocol, a translator IC must be included to generate RS-232 voltage levels. Such an IC can use a lot of power, so any chip selected to perform this operation must be power-wise and support a micro power mode when no cable is connected. When there is a cable connected to the device, a cable detect signal must be sent to the MCU. The device must support standard baud rates between 9.6k and 115.2k baud.

3.2.8 ZigBee Communications Module

The ZigBee Communications Module is present to satisfy the requirement for an embedded ZigBee Mesh radio. For this design, due to the imposed time limit and development costs, it was determined that the purchase of an existing ZigBee platform was appropriate. This reinforces wireless interface-ability by starting the design with a working radio. This module must communicate through a UART or SPI port. The module must be FCC approved and able to communicate up to a mile. It also needs to be power conscious, using less then 30mA when receiving data. Finally, the module must support firmware changes enabling the swapping of network personalities.

3.2.9 External Flash Module

The purpose of this flash module is to provide space for non-volatile memory storage for logs and other critical files. This module must be able to store at least 40,000 data points. This will allow a device with six sensors measuring at one hour intervals to measure up to nine months. It also must have at least 250 Kbytes for other data. The actually IC selected must communicate using SPI.

3.2.10 Removable Flash Memory Module

This module is present to satisfy the requirement that a common flash memory card interface be supported in this project. Possible memory cards available for consideration are: CF, MS, SD/MMC, and xD. The type of memory card used must support an auto-detect feature when cards are inserted in the memory slot, capacities of 128MB to 2GB, and interface using SPI. The selected card type should be easily accessible by the public and cost less than $30.00 dollars. Lastly, the card type needs to support hot-insertion and removal.

3.2.11 User Interface Module

The general requirements state that the device must have an LCD-driven user interface that simply and quickly allows a user verify correct operation and access device configurations. In conjunction with the display, 10 push buttons must be included to navigate through screens. These buttons must support push/hold button interpretation for slow-fast behavior for scrolling and field editing. The screen must be easy to read/interpret and avoid cryptic readouts. Consideration must be taken for future multi-language support.

3.3 Firmware Breakdown

The design of the firmware was also done in a modular fashion. However, the delimitation of the firmware modules was not done strictly based on a functional breakdown of the system requirements. Instead, it was based on how much hardware detail was needed to execute an operation or perform a specific function. The varying amounts of detail placed different operations into different layers. These layers, depicted in fig. 3.2, are as follows: hardware abstraction layer (green), memory management layer (blue), networking layer (yellow), operating system layer (red), and the application layer (purple). The purpose for a design like this is portability. The code written for this project can be used in the future for other projects. This frees up a future designer to pick hardware without strongly considering previous projects. Specifics of these layers and how they help satisfy the overall design requirements is contained in sections 3.3.1 to 3.3.7.

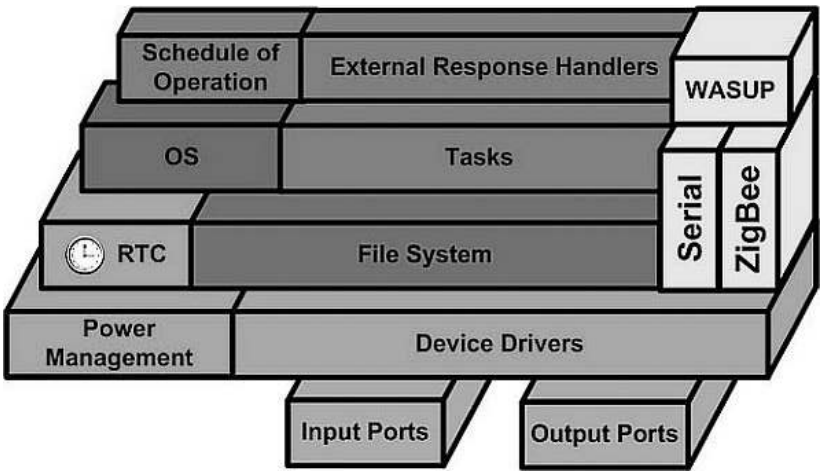

Fig. 3.2: Depiction of the general firmware design.

3.3.1 Hardware Interface Layer

The Hardware Interface Layer consists of modules that form the basic building blocks of the entire firmware set. This layer should answer how a specific operation called by high level tasks resolve into hardware action. All platform specific detail must be contained herein to promote portability.

System Power Management

The purpose of the power management driver is to provide low-level support for intelligent power supply handling and system clock handling. It must provide a means of registering speed and power needs of the device and intelligently activating or deactivating the appropriate resources. The module must shutdown the entire device when no needs are registered.

RTC

The RTC functions as the heart beat of the entire system. It must not be stopped at anytime during the product's lifetime. This code must utilize a timer resource with interrupt capabilities, time register(s), and a periodic interrupt service handler that updates the time

register(s) appropriately.

Device Drivers

The device drivers represent most of the device specific code in the firmware. Support for all hardware features are found here. The only requirement for this module is that the feature functions correctly with as little resource use as possible. Below is the list of drivers that must be elaborated on:

1. **Serial Communications-** Driver must contain handlers for transmitting and receiving using one of the MCU's UARTs. Drivers must support low-overhead interrupts to accomplish full-duplex data transfers. This driver is allowed one static buffer to store received data. The drivers are responsible for encapsulating messages with cyclic redundancy checks (CRC) for error detection.

2. **ZigBee Communications-** This driver must handle the low-level UART communications supported by the MCU. It must also format and interpret any messages to be used by a ZigBee radio. Other support for radio commands and radio updates must also be defined.

3. **Removable Flash Memory Disk Controller-** This driver must contain all the necessary disk I/O functionality so that the file system layer can access the disk. This may include functions to activate, deactivate, read, write, erase, and format the disk.

4. **SDI-12 Communications-** Driver must support message passing compliant to the SDI-12 V1.3 specification.

5. **Analog Measurement-** This driver must operate all hardware necessary to convert analog signals to digital values.

6. **Digital Measurement-** This driver must operate all hardware necessary to characterize digital signals. This may include timer and capture/compare hardware manipulation.

7. **LCD Screen-** This driver must support functions like activate and deactivate display, initialize screen, write characters, move curser, and clear screen.

8. **Push Buttons-** This driver handles the de-bouncing and behavior of the buttons. The final output of this driver is that a particular button was pressed. This result is found by integrating a timer and external interrupts. Finally, the driver must support multi-rate button responses.

9. **Internal Flash Memory Controller-** This driver enables access to code memory space. This is used for firmware updates and non-volatile configurations storage. The driver must support writing and erasing on memory sizes smaller the one flash block.

10. **Serial Flash-** This driver must handle the low level USART communications supported by the MCU. All memory operations (reading, writing, erasing, checking status, etc.) must be accessible. This drive must format and interpret data packets appropriately.

3.3.2 Memory Management Layer

The Memory Management Layer abstracts the specifics of the memory drivers and promotes memory access to a file level. Not all of the existing memory in system is required to be under the control of this layer. Only memory that is available for application use or is meant to be externally visible must be managed here. There must be two different file types specified for this system. The first is part of a low-overhead, proprietary file system used by Acclima. The second is standard FAT16/32 file types [35].

Acclima File Type Support

There are a number of files that are specified for this layer. Following is a brief introduction to these files and their purpose:

1. **Factory Configuration-** This file contains the information about factory settings, calibrations, and product creation. It is located in the internal flash of the MCU and is 256 bytes long.

2. **Device Configuration-** This file contains the information about the current settings for the device. Active sensors, passwords, owner information are also contained in this file. It is located in internal RAM and takes up 512 bytes. This file also has a shadow file located in Internal Flash. It is not externally accessible and is used to verify correct device operation even during power failures.

3. **Firmware Update-** This file is located in external flash and is 64 Kbytes long. It is used to hold a copy of a firmware revision that will be copied into the MCU's main program space during a program update sequence. The contents of this file must pass an extensive verification processes before it is allowed to update the device.

4. **ZigBee Firmware-** This space consists of three files, a coordinator image, a router image, and an endpoint image. These three files are all 64K each and are located in external flash. The same verification process used in the firmware update file will be used here as well.

5. **Device Logs-** This file must exist in the external flash chip. It must be at least 640 Kbytes in size. Device, error, and sensor logs must be stored in this file. The file must also be circular meaning that the beginning and end of the file are not fixed at the ends of the space. This enables the easy retention of older data without expensive memory transfers. Although this file is circular, any external access to this file must appear like a normal, linear memory access.

FAT16/32 Support

The incorporation of a FAT-based filesystem into this system is required if the removable memory card is to function correctly in a PC. All files with this format are only found on the removable flash device. To use a memory card with a file system correctly,

supporting firmware must be in place to handle these file accesses. The generation of such a module is beyond the scope and resources of this project. Therefore, file system code must be obtained that will perform the appropriate memory operations. The code must be conservative both in size and RAM usage.

3.3.3 Networking Layer

The Networking Layer is responsible for information routing between multiple devices in a system. This could include a direct connection from a PC to a logger, a wireless connection between multiple loggers, or a PC to Logger connection through the wireless network. To facilitate a common multiple interface layer, all compatible devices must therefore be able to communicate using the propritary Wrapped Acclima Serial Universal Protocol (WASUP). WASUP contains a universal interface standard for use with serial RS-232, User Datagram Protocol (UDP), and Transmission Control Protocol (TCP). WASUP must be expanded to incorporate the ZigBee interface. Any WASUP message must either be processed by any recipient or sent to its appropriate destination.

3.3.4 Operating System Layer

The OS layer is responsible for system management and responsiveness. An OS can be a complex piece of management code exercising control over all system resources and dictating their access permissions. The root of any OS is its scheduler. The scheduler is the portion of the OS that dictates how to allocate the processor(s). Many styles and methods of schedulers have been developed to meet the needs of embedded system. Cooperative vs. preemptive, dynamic vs. static, priority vs. round robin, and table-based vs. link-list task queues, just to name a few.

This device requires a scheduler that will be able to manage multiple operations or tasks. The completion time of these tasks vary from less than 50ms to one minute. After weighing the performance and size specifications of the existing OS platforms, it was deemed that they either required too much memory to operate or provided services that were unnecessary for this device. Therefore, it was determined that a new OS would be

created for this design. The new OS would have the following requirements:

1. The scheduler must be table-based. Table-based schedulers use a fixed amount of memory known at compile time. They are also deterministic, helping to guarantee the timeliness of any given response.

2. The scheduler must select tasks cooperatively. While this does minimize OS complexity, this requirement can reduce the overall response time of a externally triggered task. Therefore, external event handling must be treated as an exception to handle time-critical responses.

3. All operations deemed time-critical must take less than one millisecond. Tasks must also report to the scheduler the worst case execution time of the currently running task. This will allow the OS to report to an external request the duration of time to wait before assuming a request failure.

4. All tasks must use a shared address space. Therefore all tasks are required to cleanup utilized memory. The OS is not required to define any form of memory protection.

5. All operations taking longer than one millisecond or using a key system resource must be designated as a task and must run in conjunction with other tasks as dictated by the scheduler.

6. The OS must support variable levels of activity. These may include sleep, reduced operations, and full operations mode. The OS must utilize the Power Management Module to correctly perform this function.

3.3.5 Application Layer

The application layer is the most coupled layer to the environment. It handles the behavior of the device and dictates responses based on stimuli percolating from the layers previously discussed. This layer contains the logger abstraction. It utilizes OS tasks as well as using fast interrupts to respond to external stimuli to encapsulate the device's overall behavior.

Atomic Handlers

The interrupts of an MCU must be used to handle communication transfers, to queue up tasks called on by the devices environment, and to service an internal device need. All of these operations must be fast ($< 1ms$) and must not be interruptible. The events that fall under this designation are:

- **ZigBee Communications-** Any form of communication between the ZigBee Radio and this device must use this handler. This routine must work with this interface on the byte and packet level. When a packet is ready to be serviced, it must then schedule the appropriate task to service the packet.

- **Serial Communications-** Any form of communication coming through the serial port must use this handler. This routine must work with this interface on the byte and packet level. When a packet is ready to be serviced, it must then schedule the appropriate task to service the packet.

- **Serial Cable Detect-** When a valid connection is made using a serial cable, this handler must ready the processor for communications by registering required power modes with the system. When the cable is disconnected, this handler must remove the imposed power modes and allow the system to sleep.

- **Removable Flash Detect-** When an insertion or ejection event is detected, this handler must be called to either setup or clean up the card and file system status registers.

- **Push-Button and De-bounce-** When a button press is detected, this handler must observe the triggered signal for a reasonable de-bounce period after which it must schedule the appropriate task with the OS.

Scheduled Operations (Tasks)

This section illuminates the tasks required to satisfy the general requirements for this device. The priority ratings and their corresponding task assignments are: low (31-63), medium (15-30), and high (0-14).

Tasks that must be designated high priority are:

- **ZigBee Network Initialization-** To save battery power, the ZigBee radio will not be powered all the time. This task must be called every time the radio needs to establish its network. When this task is allowed to run, it must activates the radio and detect the radio's current network function. If the radio detects it is a router or endpoint, then the initialization task exits. If the radio detects that it is the coordinator, the device must retrieve any new data from all members of the network.

- **ZigBee Communication-** This task must handle any traffic that comes through the ZigBee radio to this device. This traffic could consist of network initialization packets or general WASUP communications.

- **Serial Communications-** All communications from and to the serial port must be routed though this task.

- **User Interface-** Any calls to change or update the LCD screen via the push buttons must be done in this task.

Tasks that must be designated medium priority are:

- **System Status-** This task must periodically update system status information. This information is then accessible for recording or viewing at will.

- **Removable Memory Initialization-** This task must register that the memory card has been inserted into the system, validate card properties, and verify that a FAT file system is in place.

Tasks that must be designated low priority are:

- **Sensor Measurement-** Since this device is functioning as a data logger, it requires a range of sensor measurement tasks. All measurement tasks must be scheduled independently; therefore a task is required by every sensor.

- **Configuration Backup-** System configurations must be periodically saved in a "shadow file" to increase system fault recovery. If a fault is detected, the backup will replace the corrupted configurations.

- **Device Sleep-** This task has the lowest priority and must be scheduled when no other task is ready. It can shutsdown all parts of the device based on the current operating requirements.

3.4 Enclosure

From the device features listed in section 3.1, the enclosure must be weather proof and have a lock. The enclosure must be made of ABS plastic that has UV inhibitors that reduce the breakdown of the plastic in sunlight. It must incorporate the LCD screen, radio antenna, removable memory card slot, and buttons. Figure 3.3 shows a computer generated model of the prototype enclosure.

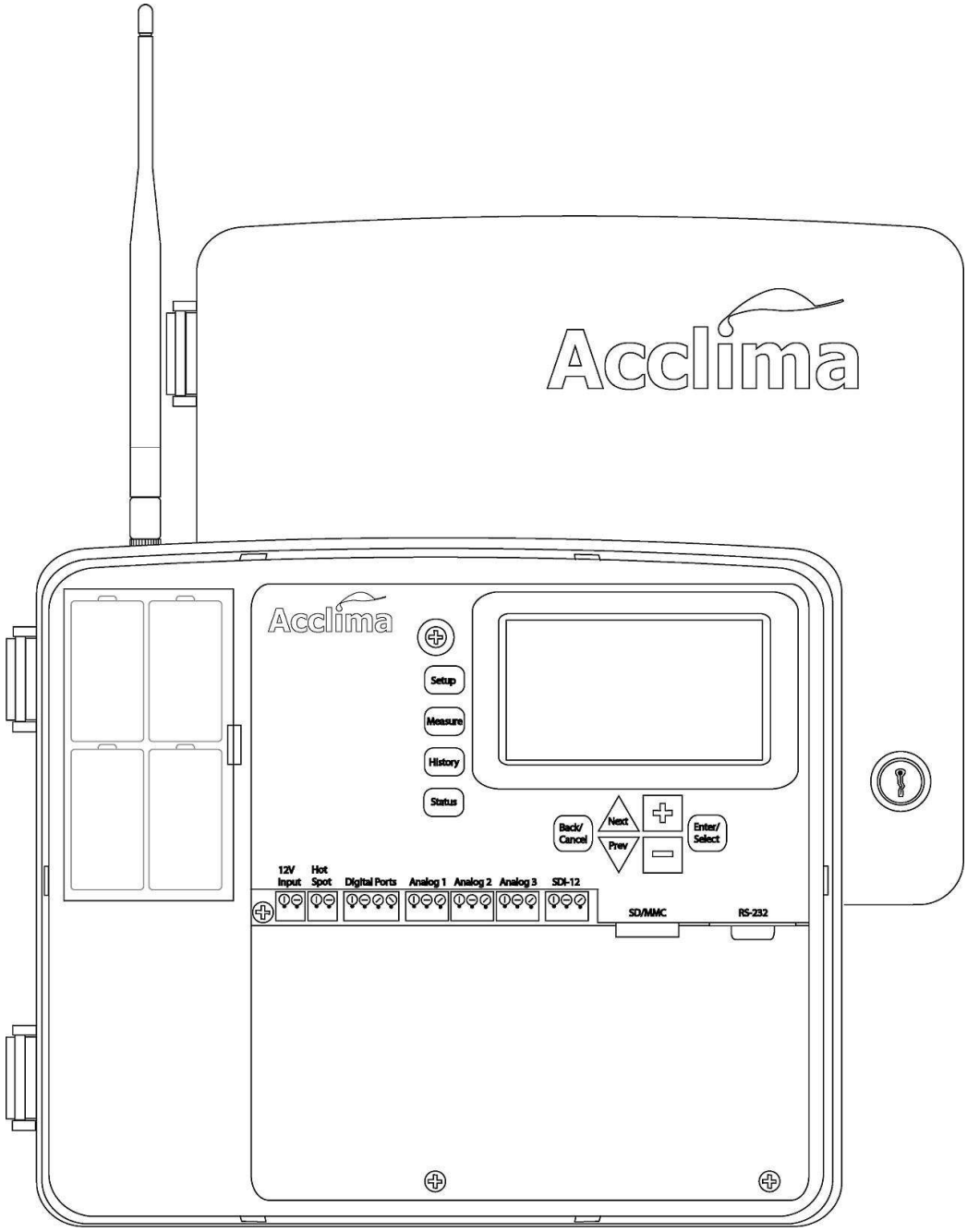

Fig. 3.3: Artistic depiction of the *Acclima DataManager's* enclosure and front panel.

Chapter 4

Implementation

This chapter discusses the implementation path taken during the course of this research and project development. The requirements and elaborations expressed in Chapter 3 were used to guide the selection of available hardware components. The selected components were then assembled and specific operations verified. Once the verification process is complete, the resulting device's performance and functionality was tested. These test results are shown in Chapter 5.

4.1 Hardware Analysis and Selection

The analysis of constraints or requirements that took place to realize a satisfactory hardware solution is contained in this section. The implementations of all the modules depicted in Figure 3.1 are discussed here. Primarily, this section focuses on the tradeoffs made during this phase.

4.1.1 Power Supply

To realize the hardware input and output requirements of this module, multiple IC's and technologies needed to be combined. Figure 4.1 shows the selected combination of components. On the input side of this module, there are two separate input sources. Both could supply power at any given instance, therefore the reverse voltage protection (RVP) circuit must guarantee that each supply does not interfere with the other. All components directly connected to the RVP circuit must normally operate in a range of 3.0-15.0 V. These devices include a 3.3 V low drop out (LDO) linear regulator, a 3.3 V switching regulator, an adjustable-output switching regulator, and a battery supervisor circuit. The 5.0 V LDO is connected to the output of the variable switcher, and therefore must be able to operate

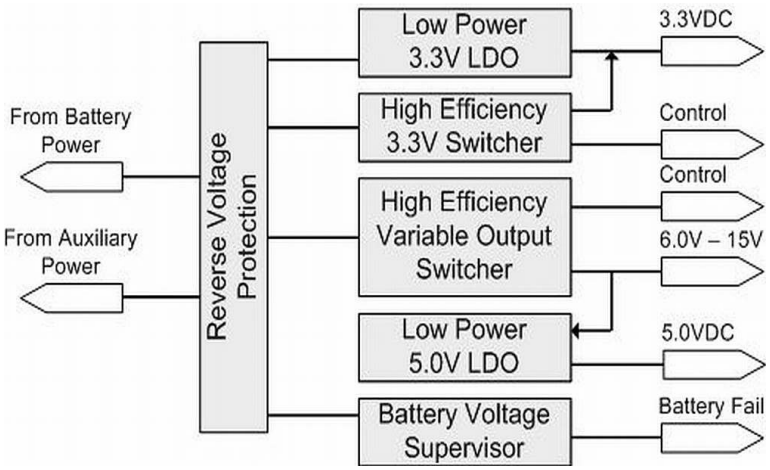

Fig. 4.1: Diagram of the power subsystem.

with inputs ranging from 6.0-15.0 V. The switchers have the ability to be deactivated using control lines. The battery supervisor circuit sends a digital signal when the power after the RVP circuit drops below a minimum threshold. In sleep mode, the entire power supply consumes 13.2μA.

Reverse Voltage Protection Circuit

This circuit traditionally is a diode placed in series between the positive input and the voltage regulation devices. An inherent characteristic of diodes that can be problematic in low power applications is that diodes have a forward voltage drop of 0.7-1.5 V. This reduces the total available voltage from the battery pack, thus reducing operational lifetime. This is not so crucial for the auxiliary power port, but it is a concern for when operating from the battery pack.

In an effort to extend the life of this product, the designers searched for ways to get around this dilemma. A resolution was found by using two HexFET power transistors [36] in series with their gates tied together. This resulted in a circuit with a switch-able diode-like behavior with a 50mV drop. Figure 4.2 illustrates the back to back transistors with supplementary BJT transistors that serves as an auto-select feature when the "power select" signal is eithier not driven or is tied low. If the control line is driven high, the circuit switches off the path from VBAT to VIN. Comparing this drop to a standard diode, the battery life

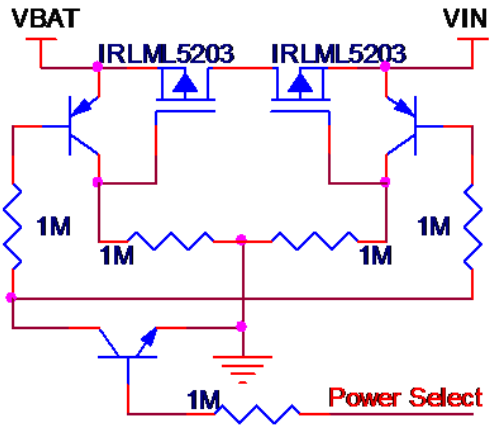

Fig. 4.2: A schematic representation the reverse polarity protection circuit.

was extended an estimated three weeks to two months. The ability to switch the circuit's behavior from an open circuit to a diode also allows both ports to be powered at the same time. When the power on the auxiliary port is $4.5\,V$ or above, the battery pack will cutout and the auxiliary port will supply all power needs. If power on the auxiliary falls below $4.2\,V$, the battery pack will be switched back in with no power glitches.

Low-Power LDOs

The LDO regulator chosen here is TI's TPS715XX [37]. It comes in a regulated $3.3/5.0\,VDC$ output at $50mA$. The regulator's quiescent current is $3.2\mu A$. Reasons for this selection are that it matched performance requirements, low cost, and was already in Acclima's stock.

3.3V Switcher

After extensive review, TI's TPS62110 [38] synchronous buck switcher was selected to perform this function. It is rated to be 95% efficient within the operating ranges of this device and has a quiescent current of $2\mu A$.

Variable Output Switcher

This device by far took the most energy in this module. The complexity in this decision stems from the need to produce 6, 9, 12, and $15\,V$ when the input voltage could drift above or below the output voltage. This device must therefore step up and step down voltages. The three types of switchers that can regulate above, at, or below the input voltages are buck-boost, fly-back, and SEPIC[1] regulators. A buck-boost regulator has an advantage if the application needs a negative output voltage. Fly-back regulators can be used in the DC converter mode or as an AC transformer. Both modes are subject to very high voltage spikes. SEPIC converters do not invert the power signal and provide a true "power off" state with no leakage.

The SEPIC converter was selected as the regulator of choice. Finding one that performed with the desired input, performance, sleep, and output specifications turned out to be very difficult. The solution taken in the end was to use the LTC1871 [39]. This device is 80% efficient but does not satisfy the sleep requirement because its sleep current is $10\mu A$. To meet power requirements, a power switch was added to the input power line to this device to completely remove it from calculations.

Battery Voltage Supervisor Circuit

This circuit posed a challenge in finding parts that operated at less than $7\mu A$. Most were $15\mu A$ parts with desirable features like hystorisis and a wide input voltage range. The part selected to supervise the battery voltage was the TPS3803-01 [40]. This chip has an internal reference, a difference amplifier, and an active low open drain output. This device uses an incredible $2\mu A$ to operate. However, the input sensing voltage maxes out at $6\,V$. The device also has a $30mV$ hystorisis. Both these apparent drawbacks were resolved by using the TPS3803-01 as a part of a hystorisis generating circuit. This circuit modifies the input voltage and adds a variable amount of swing to the voltages to trip the supervisor's reset signal. The total circuit uses $4.7\mu A$.

[1] Single-Ended Primary Inductor Circuit.

4.1.2 Controller

The selection of an MCU requires much study and analysis of the design needs. Two items of note when selecting an MCU is that there is an inherent tradeoff in power and performance, and there is a general cost increase as the MCU grows in pins, peripherals, or data-path size (8-, 16-, 32-, or 64-bit).

There are as many as 30 manufactures and thousands of different MCUs to choose from. Therefore, it is critical to filter out MCUs with unnecessary features. The first step was to remove any devices with higher power and performance ratings than required. The next filter applied focused on power saving features and low power use options. This practically removes all devices with 32- and 64-bit cores and restricts this design to 8- and 16-bit cores. The drawback to this restriction is that most 8/16-bit MCUs have an internal memory map (Flash + RAM) based on 64K bytes max. So the application must fit in a space less than 60K bytes. This was accepted as a reasonable limitation for this application in the initial phases of desgn.

The residual list of processors was still varied. So parameters like cost, required peripherals, and memory size were included in the search criteria. This adequately reduced the number to three specific microcontroller families: Microchip's PIC18, Atmel's ATmega, and Texas Instrument's MSP430. Based on previous experience, the designers rejected the PIC18 family because the memory architecture used banks instead of having a unified memory map. This complicates development and reduces the performance of a processor. The ATmega64 MCU has an 8-bit AVR core that attains nearly $1 MIPS$ while running at $1 MHz$. The MSP430F14X has is a 16-bit RISC core that also boasts $1 MIPS$ at $1 MHz$.

Both MCUs have all necessary features designated for this project. The major difference and one of the key reasons that the MSP430 was chosen is that the MSP430 can potentially do twice as much work as the ATmega64 while consuming half the power. The MSP430 uses approximately 500 μA when running at $1 MHz$. Another reason the MSP430 was chosen is that it had an internal $1.5 V$ and $2.5 V$ analog reference that was rated to 1% accuracy. It also has a 12-bit SAR-cored ADC. The ATmega64 has a 10-bits SAR. Finally the MSP430

was chosen because the designers already had experience using it and no extra expenses would be necessary to acquire the tool suite necessary to develop with this processor.

The selection of the MSP430F14X [41] does have two drawbacks. First, the code size is limited to 60K bytes. The data manager application is moderately complex, but the engineering team estimated that this application will not exceed 60K bytes. Second, the largest chip size available is 64 pins. This does not directly satisfy the I/O requirements. Therefore, all control signals must be routed though multiple latching octal-line drivers.

4.1.3 SDI-12 Communications

The SDI-12 specifications require a $12\,V$ power line, a $5\,V$ bidirectional digital communication line, and a ground line. The power line comes directly from the SEPIC switcher through a power switch. The SDI-12 protocol specifies using an asynchronous 1200 baud signal with seven data bits, even parity, and one stop bit in a byte packet. The selected MCU does not have a spare UART to run this communication sequence. Therefore, the message passing will be done using a timer assisted capture/compare port (CCP). This port set a logic output or sampled a logic input based on a 1200 baud time. The only other element to consider is that the MCU ports operate on $3.3\,V$ and the SDI-12 line needs to operate at $5\,V$. To rectify this discrepancy, the SN74LVC1T45 [42] is a 1-bit, dual-supply, bidirectional line driver was used to step up or step down the line voltage. Over voltage protection was also included.

4.1.4 Analog Measurements

The analog ports were implemented using the MCU's internal ADC and references as well as other external parts. The physical terminal comes with power, ground, and signal connectors. The power connector receives its power from directly from the SEPIC switcher through a power switch. The signal port is protected from over-voltage and reverse-voltage using a zener diode. The signal then passes through a conditioning circuit. This circuit can be configured to interpret the incoming signal as a 0-20mA current loop signal or as a voltage signal. If it is a voltage signal, the signal will be processed with hardware to range

the converter appropriately. This feature realizes the required auto-ranging capabilities of this port. If the port is configured incorrectly or the signal is outside the measurable range of the device for any particular setting, the port also has shunt diodes to remove the excess charge before it reaches the MCU.

4.1.5 Digital Measurements

The digital ports were implemented using a CCP and timer pair inside the MCU, and a line driver. The line driver is the SN74LVC1T45 [42] used in the SDI-12 module. The digital ports have hardware support to sample on request, record on event, measure pulse-widths, and pulse-frequency. This port is protected from over-voltage and reverse-voltage. These ports support one switch-able power port.

4.1.6 Serial Communications

To comply with RS-232C, a MCU UART communication port was selected to drive the full-duplex asynchronous message passing. This was coupled with a MAX3221 [43] RS-232 level translator IC. Two excellent features the come with this chip include auto-shutdown when no line is connected and a valid signal to alert the MCU that a device is connected to the other end.

4.1.7 ZigBee Radio

The radio module selection process looked at ZigBee radios from Cirronet, Maxstream, Radiotronix, and Aerocomm. These companies are the four leading developers using ZigBee technology. The different companies vary in their base technology from Freescale's two chip ZigBee solution to Ember's or Chipcon's SoC ZigBee solution. Every one of these companies offers distinctly unique solutions that target different end applications. However, all four modules failed to fully satisfy the needs of this project. The SoC systems are recent developments in the ZigBee market and boast power ratings of $300\mu A$ active, $27mA$ RX, and $169mA$ TX. However, these solutions are not fully released to the public and bugs are still being worked out of the products. The older and more stable Maxstream XBee-Pro

Fig. 4.3: Picture of the Maxstream XBee-Pro radio module.

module used $30mA$ active, $55mA$ RX, and $215mA$ TX.

The crucial requirement that the radio's network function (i.e., coordinator, router, or endpont) be dynamically allocated led designers to select the Maxstream XBee-Pro [44] (see fig. 4.3). Its power consumption makes is a non-ideal solution. However, Maxstream has certified the *DataManager* and its development and given intellectual rights to allow this device to reconfigure their radio. This level of cooperation and customer service also encouraged the designers with this selection. However, as better ZigBee products become available, the device will migrate to support a more ideal solution. The XBee-Pro uses a standard UART to communicate to its host. Therefore, the second UART on the MCU was dedicated to the radio.

4.1.8 External SPI Flash

The common sizes for inexpensive SPI flash are $2Mbit$ (256KB), $4Mbit$ (512KB), and $8Mbit$ (1MB). Two different chips were found that satisfied the operational and sleep mode functional requirements. Both have similar interfaces and are 8Mb in size. One of these devices is Atmel's AT45DB081X [45]. It claims a 2-10μA sleep current and $4mA$ read and $15mA$ write current. The other device is Spansion's S25FL008A [46]. This part has a .2-5μA sleep current and a $1.5mA$ read and $7mA$ write current. Both chips cost about a $1.20. The Spansion part was selected over the Atmel part. However, there were some reservations

as to the stability of the Spansion part. So both chips were included in layout to provide redundancy.

4.1.9 Removable Memory

Secure Digital [47] (SD) and Compact Flash [48] (CF) are two of the most popular and widely available forms of removable flash memory. The other considerations for removable flash memory were rejected because any implementation detail requires fees to be paid to the individual flash memory institution. CF cards use a total of 60 pins to interface to a host. Technically, only 20 are needed to interface in its smallest supported mode. It can appear to operate as an IDE disk drive, memory-mapped storage, or I/O-mapped ports. A big drawback in its basic operations is that is uses parallel address and data busses. This is very fast, but the MCU cannot support this interface. The SD interface has nine pins and supports five modes: SD0-SD3 and SPI. The SD0-SD3 modes support a 1- to 4-bit parallel interface. The SPI mode is compliant with the SPI communications module supported by the MCU. This is a three wire interface and all card features are still fully accessible.

The SD card was chosen as the preferred type of removable memory. Local stores currently carry 512MB or 1GB for about $15. For some perspective, 1MB is enough memory to hold three months worth of data generated by a device with six sensors sampled every 15 minutes. At this rate, 512MB could record data from an entire network of 32 loggers for one year.

4.1.10 User Interface Module

Two types of screens were considered for use one this project: a custom LCD display, or a LCD character display. Acclima has had experience in the past with making their own custom glass. Figure 4.4 shows the first attempts at the artwork for the custom LCD. All black symbols represent segments that would be activated individually. This screen would need a 128-segment LCD controller. Power wise, custom glass would only use 1-2mA if all the segments were active at the same time. The drawback to this method is that changes, upgrades, or supporting other languages would be expensive and units already released

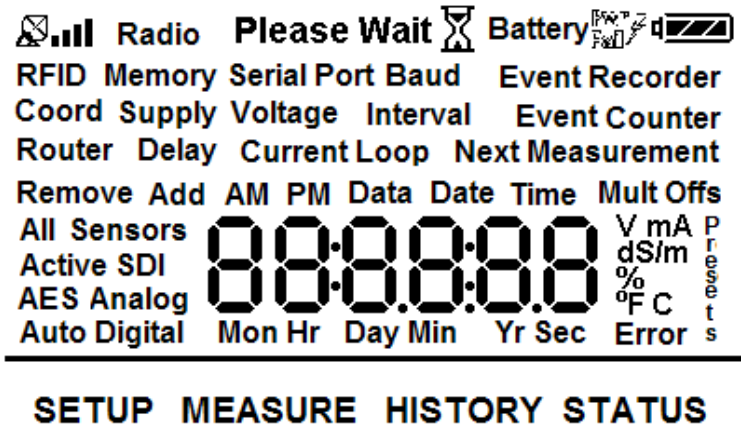

Fig. 4.4: Custom LCD glass art generated for this project.

could not be upgraded.

Character displays come in many sizes and the contents of the display are incredibly flexible. Four lines by twenty characters is the size of display that is of interest. It is big enough to be informative and small enough to be comparable in price to custom glass. It does, however, require 5VDC and 2.5mA to operate. Although the character display uses more power, the flexibility of the display was desired. The TM204JAA7 [49] was the exact part selected.

4.2 Construction

The construction of the designated alpha test units commenced May 2007. The alpha units' purpose was to verify the function of all hardware features and to build up the basic device drivers and rudimentary OS. Only six devices were constructed. Details of the testing and verification will be discussed in section 5.1. The alpha tests resulted in some changes in the design and layout of the board. These changes were minor enough to move to the beta phase of testing. This phase required the production of 75 units. During beta testing, all features were to be implemented and tested. Further, 60 of these units were shipped to a few producers and other interested parties for evaluation.

Chapter 5

Testing

This chapter focuses on the system testing that took place May 2007 through October 2007. This period comprises the alpha and beta testing portion of the project. Testing took place in Logan Utah, Meridian Idaho, and various locations in California and Washington.

5.1 Alpha Testing

The purpose of the alpha testing phase was to verify and measure the hardware's ability to performe within the specified requirements. All testing conducted here was done individually with minimum influence from other modules. Figure 5.1 shows the assembled hardware used in this phase.

5.1.1 Power Consumption

The testing revealed that the entire device sleeps less than $50\mu A$, runs around $250\mu A$ for reading sensors, $2.5mA$ when communicating with the PC, $8mA$ with the display on, $32mA$ with the radio active, and $217mA$ with the radio transmitting at full power. With these power modes and a fictitious system with six Acclima SDI-12 sensors measuring every hour and radios communication every 2.5 minutes, it is calculated that C-cell batteries with an $8{,}000mAh$ capacity could power the system for just over a year.

5.1.2 Power Ports

The system has an auxiliary power input port that can withstand up to $30\,VDC$. The original figure required was $15\,VDC$, but during the part selection process all parts related to that input had higher ratings. Consequently, this port can now support $6\,V/12\,V/18\,V$ solar power. The device also has one power port for direct battery draw and five other switch

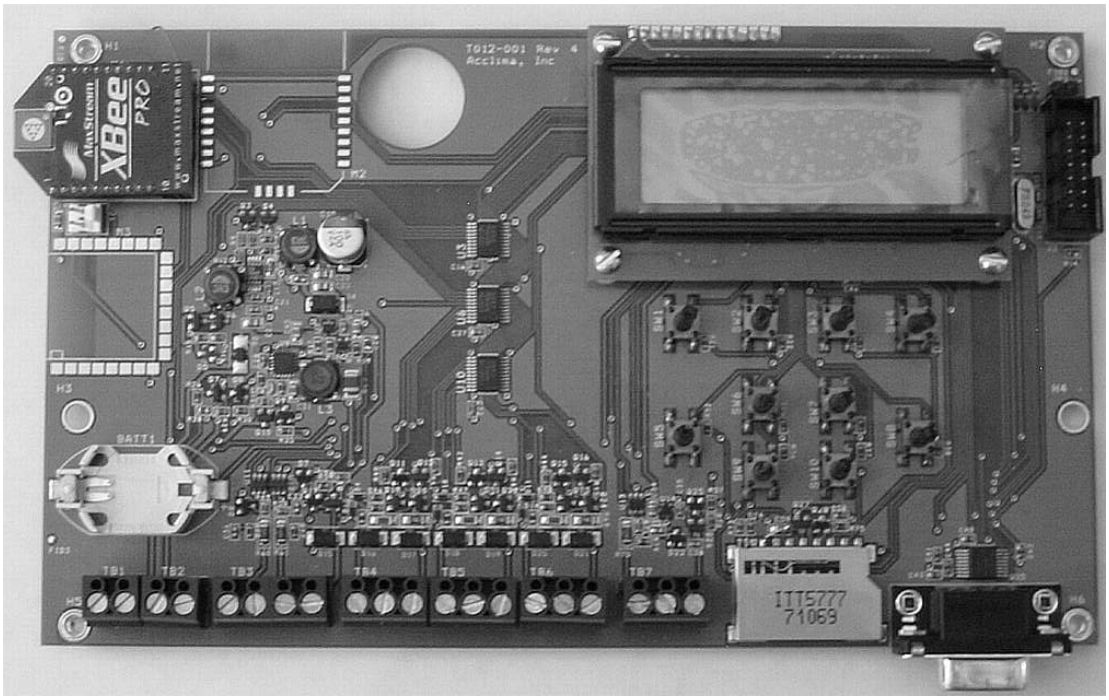

Fig. 5.1: A depiction of the test platform (circuit board shown).

power ports for sensors. The switched ports support $6\,VDC$ at $500mA$ through $15\,VDC$ at $200mA$ output.

5.1.3 Cost

The production cost per unit is around $150. This places the *DataManager* list price around $650. This is below the required limit of $800.

5.1.4 Time

The device contains a real-time clock (RTC) with battery-backup for unbroken time-keeping for longer than five years with no batteries. The system draws $3.4\mu A$ in backup mode. With this draw and a $300mAh$ lithium coin cell, the device is estimated to have backup battery lifetime of ten years.

5.1.5 Versatility

The device supports all of the following interface options: one SDI-12 communications

port adhering to version 1.3, three 12-bit analog input ports with an auto-ranging voltage input capable of measuring 0-10 V and 0-20mA current loop measurements, and two digital measurement and I/O ports. All sensors are capable of being configured separately and can measure with one minute resolution.

5.1.6 Communication Interfaces

The device supports an RS232 serial interface and an embedded ZigBee Mesh radio interface. Both interfaces are coupled with the WASUP message passing protocol which supports inter-device networking through multiple physical mediums. In the case of ZigBee, WASUP coordinates message passing and automatic routing for centralized data storage and inter-device communications.

5.1.7 Removable Data Storage

The device supports a SD card interface for extended memory applications. The insertion and removal of the card is detectable and permitted while the device has power. Card sizes of 2GB and below are supported. Advanced security features of the SD card are also not supported.

5.1.8 User Interfaces

The device has two easy-to-use methods for configuring operations. One method is to use a LCD driven user interface. No PC or handheld computer is necessary to access device function and to verify correct device operation. With an SD card, data storage functions are also fully available. The alternate method using PC software is able to interface to a logger using the serial port. The software can also connect to a network of loggers using the ZigBee network. The software handles the database operations on all the data collected by all nodes in a given system.

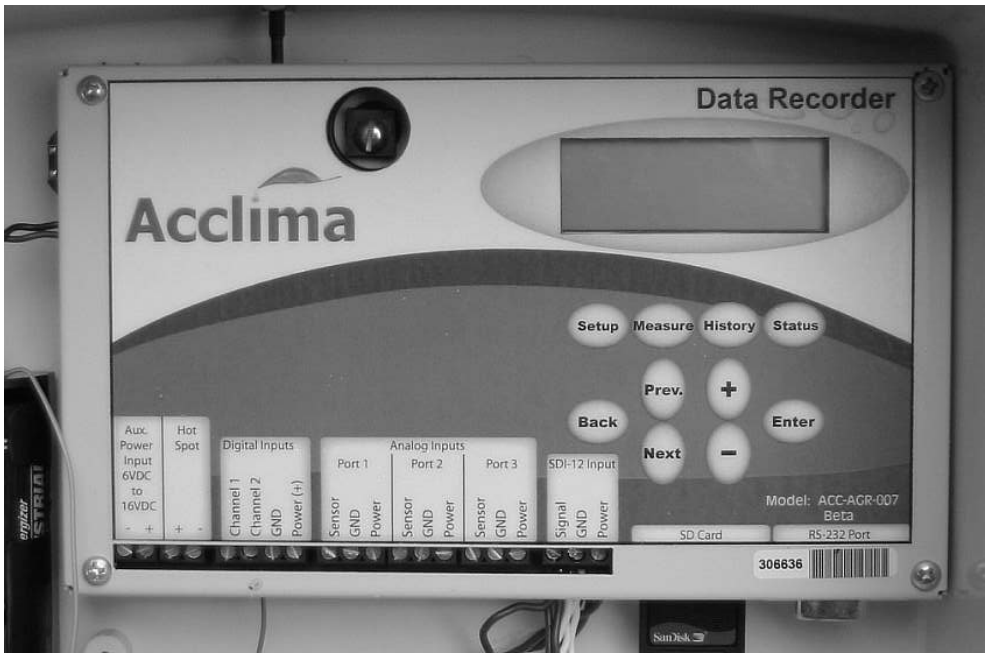

Fig. 5.2: Beta test hardware (covered by face plate).

5.1.9 Ruggedness

Each device comes in a weather proof enclosure and has a built in lock. All connection ports are ESD protected. The device's enclosure is not capable of handling submersion.

5.2 Beta Testing

The purpose of the beta testing phase was to test the devices various feature sets together in varied stages of completeness. The beta testing was broken down into three distinct phases. Phase one's purpose was to test a stand-alone device supporting one SDI-12 sensor, the scheduling framework, and basic WASUP communications to connect to the PC. Phase two tested all sensor interfaces, the SD card, and LCD user interface. Phase three tested the ZigBee radio network and advanced WASUP options. At the end of the third phase, the testing of all features would be complete and the device would be ready for its production review. Figure 5.2 shows the assembled circuit board cover inside the enclosure that was used during this phase.

5.2.1 Phase One

This is the first phase that others outside of Acclima were brought in to judge performance and to help identify bugs. At this stage, the device need only support one SDI-12 sensor, the framework for the data logging scheduler, and basic WASUP communications. Operations testing for SDI-12 devices included querying, change of address, adding, identifying, measuring, and removing one sensor. All this testing was done using the device configurations and scheduler. Screen options allowed for configuring and reading the sensor. The basic WASUP interface was also in place to permit the PC to adjust device properties and configurations.

The major problem identified with the Data Manager at this phase was that 60% of all units failed to add or read a sensor. The problem occured because the internal resistance inherent in battery packs limited the instantaneous current surge required to charge up the SDI-12 power line. This in turn caused the battery voltage to drop and the supervisory circuit triggered a reset. This problem did not surface during alpha testing because the device was being powered by bench power with sufficient supply. Three actions were taken to remove this bug. First, the battery supervisor interrupt was momentarily disabled to allow for these dips during a sensor power up sequence. Second, the power supply was redesigned to limit the surge current to a greater extent than the batteries. Lastly, system and error logs were created to aid in post-mortem analysis of device failures. This should assist in the search process for other possible bugs.

5.2.2 Phase Two

At this stage, the device needed to support all designated sensor interface types and a full complement of sensors, all LCD screens, and the SD card drive. The SDI-12 port was expanded to handle the addressing of nine sensors. All analog and digital ports were also fully integrated with the screens required to add, configure, and directly read sensors. The SD card interface supporting a FAT file system also needed to be in place. The SD card interface can format a drive and access and write to a directory structure that is recognized by PCs.

Two major problems arose during this phase. The first bug showed itself during the first few days of testing. After operating for a full day or when an SD card was inserted into the device, the system would crash. An easy fix for this is to trip the battery reset and the system would start up again. But the system would then become sluggish and non-responsive at times. After many attempts, the PC software retrieved the log file and configuration file from the device. The logs were replete with sensor measurement errors. The sensor causing the error was a previously un-configured digital port. However, looking at the configuration file it became apparent that the last quarter of the file had become corrupted. The culprit was some of the new code that was causing the stack to overflow into the neighboring configuration file. This problem was fixed by optimizing the stack usage and adjusting the global variables declared to reflect a more space-wise emphasis. The allowed stack size grew from 376 bytes to 516 bytes. This is enough to guarantee no further problems with the stack.

The second problem that surfaced during this phase was that the application reached the code space limit of the MCU. The final code size came to 67K bytes with over 13,000 lines code. This means that the current platform has insufficient memory for all of the desired functions this product. The radio functions and operation require about 10K bytes more. For a short term resolution, the Data Manager will come with two possible firmware applications. One supports all LCD screens and the other will support the radio. For long term, a new microcontroller will need to be selected and a new platform redesigned around this IC.

5.2.3 Phase Three

The final stage of testing required the product to support all radio operations. This included network personality changing, automatic mesh network creation and device synchronizations, computer-to-network pass through operations, and radio power management. The novel ability to change the role of a particular network node is practically unattainable for most ZigBee radio modules. This device contains images of the radio's personalities and re-flashes the radio as necessary. When a network starts up, the radios automatically

establish their mesh hierarchy and the devices are all synchronized in relation to time and the network heartbeat. Concluding the synchronization process is the data transfer that automatically directs data to a universal collection node. A PC connected to a device can then request to use the network and us this advanced connection to access other devices in the network. Last of all, the radio's signal strength is monitored and the transmitting power is adjusted to reduce power consumption but keep a good connection.

The synchronizations and surfing of multiple devices using the radios took place mainly in Logan Utah and Meridian ID during in-house tests. These features will be further tested through the end of 2007. Once a few smaller bugs were dealt with, the device and radio applications functioned correctly. It was observed that the radio network setup time was on the order of two to thirty seconds. This is longer than desired, but these limitations are imposed by the selected radio module. A future posibility is to actually design a custom radio implmentation that will give the engineers full control of the entire set of ZigBee network characteristics.

Chapter 6

Conclusions

This chapter concludes the thesis documentation for the *DataManager* project. A summary of the project's purpose and course will be reiterated. The end results produced from this research and design effort will then be set forth. Finally, this document will close with a discussion of future work in this research emphasis.

6.1 Project Summary

Interest groups like hydrological and soil scientists, agriculturalists, and large scale agricultural producers want the ability to accurately and easily collect dense spatially-representative data. No current methods could supply either desire jointly. Therefore, a new product with an integrated intelligent radio platform was proposed to satisfy the desires of these groups. This product, labeled the *Acclima DataManager* was the focus of this development. The function and application of this product was designed and elaborated upon in this document. By the completion of this development term, the product's desired functions and features were all tested and shown to investors and possible future customers. They have all expressed their continued interest in future enhancements and developments with this product.

6.2 Resulting Product

The final outcome of the *DataManager* design is too large to fit on its current hardware platform. So the *DataManager* product, seen in fig. 6.1, therefore comes in two varieties: a device with a radio or a device with an LCD screen. By December 2007, the new platform with the needed enhancements will have replaced the older platform. This upgrade will allow both currently conflicting features to cohabit the same hardware. However, both

Fig. 6.1: Final *DataManager* product with enclosure actively measuring precipitation and soil water content at a USU test site.

devices support SDI-12, analog, and digital sensors. The devices also support using SD cards for memory storage. The batteries for this system will last a year without external power. Solar panels or other forms of external power are also supported. The ZigBee radios embedded in this product are easy to enable and use. The energy required for management support of a large network of loggers has been significantly reduced. These properties allow people with a non-technical background to easily setup and operate this system. All in all, here is a device that can supply the research and the agricultural communities with a tool in which new research or monitoring opportunities can be realized.

6.3 Recommendations and Future Work

The research and development of this thesis project has left the project with two foreseeable venues for more research. First, new remote hardware units using the beta hardware will be developed. The remotes will be ZigBee Endnodes and have a feature set that is a subset if this development, making it possible for the remote's firmware to

use this MCU. The new device may not have a screen or as many sensor interface ports. It is logical to Acclima Inc. to continue this thread of development in parrellel with the full *DataManager* product. This will extend the device family to two products from this expenditure. This secondary device will function as a true distributed sensor network with the *DataManagers* as collection nodes.

The second area of possible future work is the interfacing of the Acclima's database with national databases for environmental sensing. There are many resources reaching the internet now and an interpreter program would enable many institutions to publish findings and to correlate data from other sources more effectively. With the new possibilities now available because of this research, further work can now be conducted in the topics of spatial water distributions and flux, correlating ET with subsurface data furthering refinements in remote sensing, and providing a means to achieve a level of automation in precision agriculture.

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